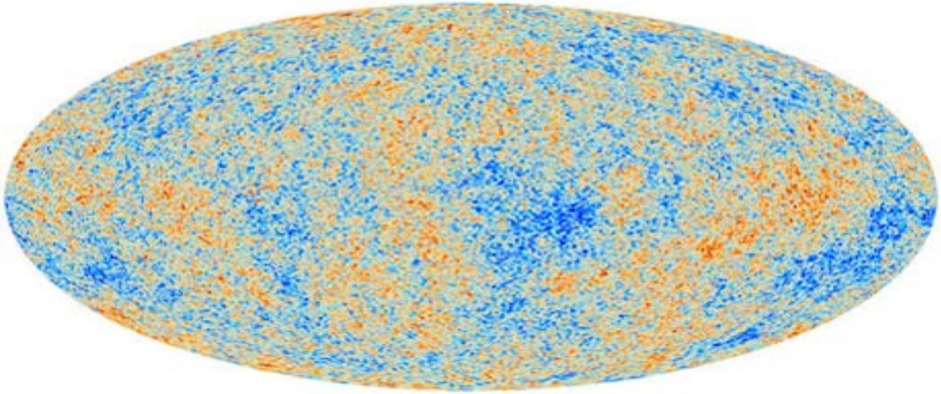
Map-making leads to understanding

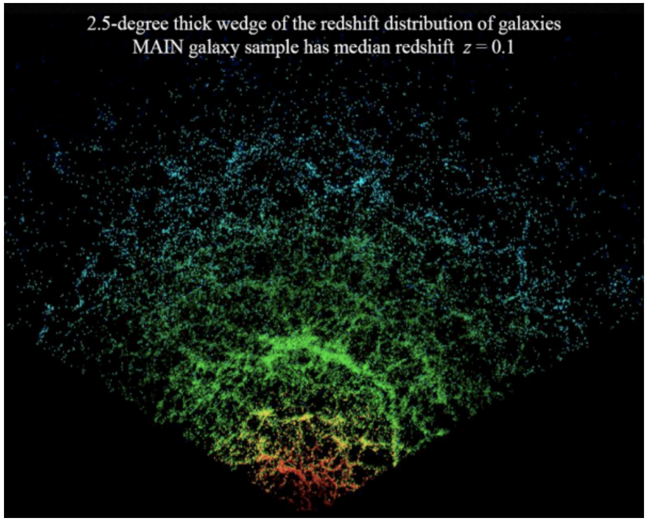
When we understand the evolution from one map to another, we can understand

- the sociological, economic, and political ***forces*** acting on the US
- the people, or the ***constituents****, of the US*

Less Parochially …

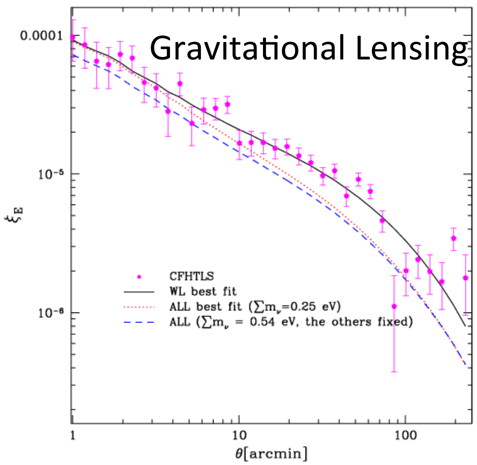


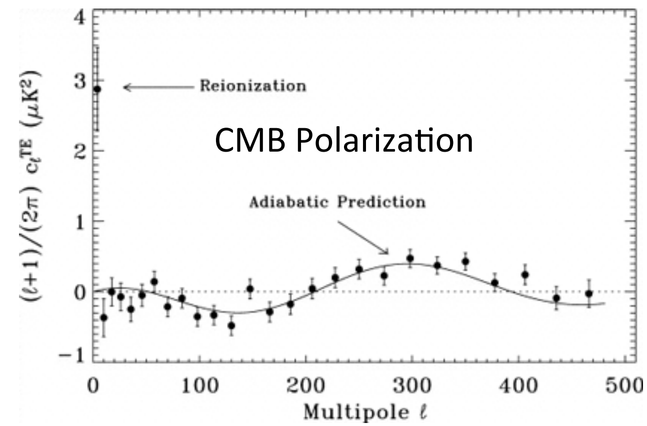
t = 400,000 years

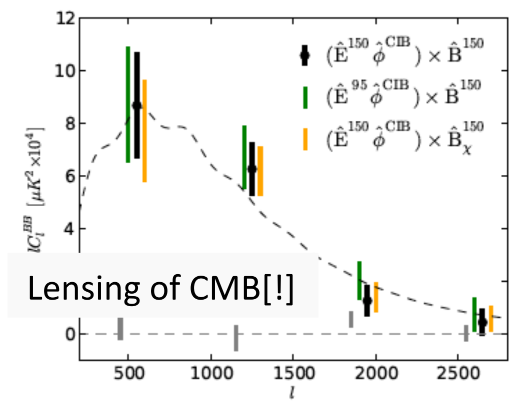


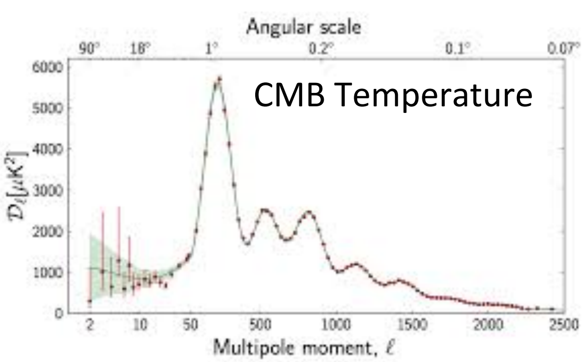
Today: Sloan Digital Sky Survey

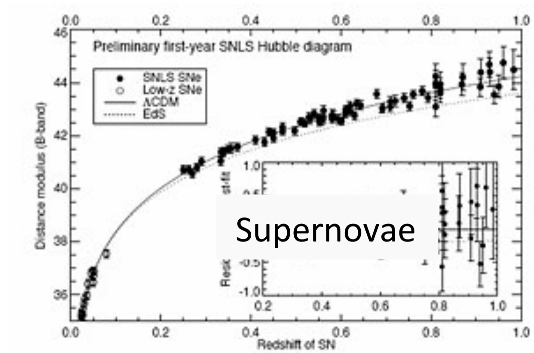
Standard cosmological model explains this evolution: Stunning Agreement with a wide variety of observations

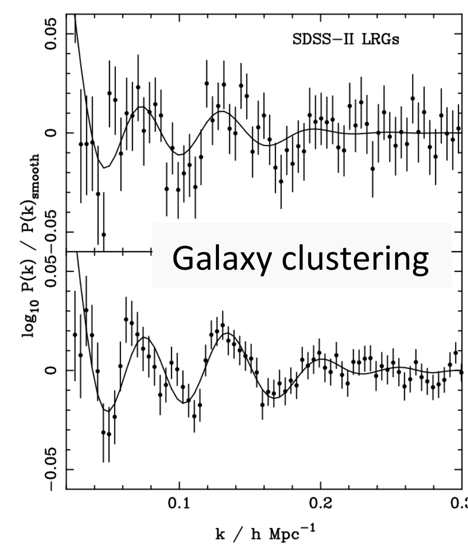












Three epochs, each dominated by new physics, are required to explain the maps

- $t \sim 10^{-35}$ sec: Early acceleration, triggered by ***Inflation***
- 300,000 years < t < 7.7 Byrs: Growth of Structure, fueled by ***Dark Matter***
- t > 7.7 Byrs: Acceleration, caused by ***Dark Energy***

Understand this new physics: strong plan internationally and across agencies often with US leadership

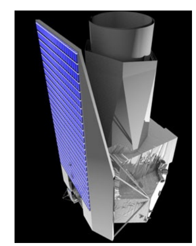
Photometric

HSC

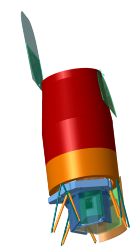
Spectroscopic

eBOSS

Euclid

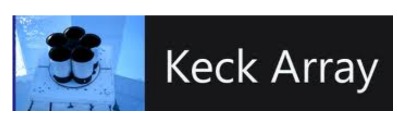


WFIRST

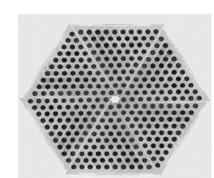


CMB

SPTPol



Stage IV



Telling you about this cosmic attack on new physics

Beyond Einstein: The Physics Driving Cosmic Acceleration (Padmanabhan) 25’

Cosmic Surveys: Extend the Reach (Jain) 15’

Tough Questions (Tolley, Kahn, Eisenstein, Wechsler) 12’

Discussion 20’

Beyond Planck: Neutrino and GUT-scale Physics from the Cosmos (Carlstrom) 25’

Tough Questions (Silverstein, Green, Lee, de Gouvea, Abazajian, Benson) 18’

Discussion 20’

Dark Energy - Why go further?

Probing Dark Energy is Probing Physics of the Vacuum!!

Scales of Dark Energy give largest Hierarchy Problem in Physics!

Gauge Hierarchy - Higgs mass quadratically sensitive to UV physics
Cosmological constant (C.C.) - **quartically** *sensitive to UV physics*

Unique connection between IR and UV physics

Consistent **low energy effective field theories** (EFT) of dark energy and modified gravity are being developed

Cosmology utilizing tools of high energy physics

Ongoing exploration of consistent stable ghost/tachyon-free EFT interactions and couplings to Standard Model and Dark Matter for **Dark Energy degrees of freedom**, Many models motivated by High Energy Physics

Equation of state **w** and **w'** are not the only probes:

Many models exhibit w close to -1 at cosmological scales but give observationally distinguishable predictions for **growth of structure.** Dark energy distinguishable from modified gravity by different relation between **Newtonian potentials**

expansion history + large scale structure, Dark sector interactions,
clusters, lensing, dynamical masses, fundamental constants at high/low redshift

CF27 and CF28

CF27. Dark energy experiments are proposed to measure w+1 to higher and higher precision. Suppose we find w = -1 at Stage IV sensitivity. What are the motivations to plan beyond Stage IV? Is there a value at which improved precision becomes drastically more difficult to obtain?

CF28. What is the target level of precision for measurements of w and w'? What do increasingly precise measurements teach us? What is next if w is consistent with -1 and w' with 0?

- There are many more parameters than $w+1$. The field is much richer than that!

- Of particular interest is that the standard cosmological model (including inflation, DE, and DM) solves so many old problems in cosmology! Its success at describing all aspects of cosmic structure formation and evolution is truly astounding.

- We have a wide range of probes, covering many scales and processes. Their mutual consistency is as important as the value that any probe gives. We need to take them all to the same level of precision to see if the consistency holds up. This requires at least going to Stage IV.

- If the simplest form of ΛCDM continues to work at the end of Stage IV, that will be even more amazing. Some of our probes will be at the end of their reach anyway (because of cosmic variance, or because we run out of galaxies). It might make sense to stop there, unless we come up with new probes of a qualitatively different character.

- Precision cosmology requires detailed treatment of systematic errors. This has been a major focus of the last 15 years.
- Astrophysical systematics are important in all cases, dominant in some:
  - *Cluster counts* and *redshift-space distortions* are currently limited by our astrophysical modeling, e.g., of galaxy formation and the impact on the intracluster medium.
  - Improved computer simulations and additional astrophysical data provides routes to improve.
- But in several cases, we are limited by experimental systematics.
  - *Supernovae* and *weak lensing of galaxies* are dominated by such issues, e.g., in flux and shape calibration. Of course, there are also astrophysical uncertainties, but they do not appear dominant at present.
  - Improvement in design and analysis requires more effort but can net substantial gains.
- Some error terms are hybrids: we could remove an astrophysical concern if we could acquire a more expensive data set.
  - Direct measurements of the *Hubble constant* and calibration of photometric redshifts or supernova circumstellar dust fall in this category.
- *Baryon acoustic oscillations* and *weak lensing of CMB* currently project to be statistics-limited even to the cosmic variance limit.

- There is no doubt that the upcoming generation of experiments (Stage IV) will be a substantial improvement in our measures of dark energy (i.e., expansion history and growth rate of structure).
- But it is also true that the cosmological returns will depend on exactly how well certain experimental aspects can be controlled and on how well certain astrophysical complications can be modeled. Forecasts are necessarily uncertain.
- Forecasts often focus only on the simplest or most conservative applications of the data. These are rich datasets with many additional dark energy handles that become usable with bolder modeling. Recent surveys have often overperformed their forecasts because of this!

Questions: Is this a fishing expedition?
What can we learn about the UV completion with one number?

B-modes: Will Cross a threshold

$r = \frac{\text{Tensor}}{\text{Scalar}}$ is related to field range

$$\boxed{\frac{\Delta\phi}{M_p} \sim \left(\frac{r}{0.01}\right)^{\frac{1}{2}}}$$

highly UV sensitive if $\gtrsim 1$

observable (at 5σ level!)

- An ∞ sequence of possible terms

$$V \to V\left(1 + \sum_n c_n \frac{(\phi-\phi_0)^n}{M_p^n}\right)$$

infinitely "UV-sensitive"

must be suppressed (e.g. symmetry)

→ Requires QG theory

→ B-modes test string-theoretic large-field inflation

Primordial Non-Gaussianity: CMB & LSS

Questions: Is this a fishing expedition?

What can we learn from one/a few numbers?

Tests the mechanism & particle content

$$\mathcal{L} \supset \frac{1}{\Lambda_1^4}(\partial\phi)^4 + \frac{1}{\Lambda_2}(\partial\phi)^2 \times \sigma + \sum_n \frac{c_n}{\Lambda_3^n}\phi^{4+n}$$

tested by non-gaussianity

tested by r

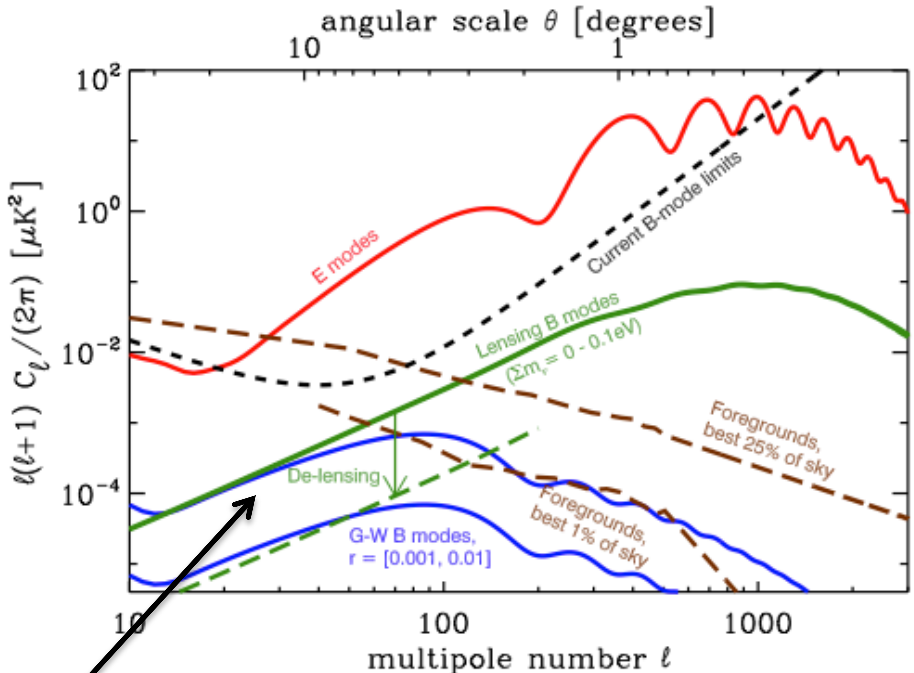
What do we learn:

Current limit

$\Lambda_1 < \dot{\phi}$ rules out slow-roll $\quad \Lambda_1 > 0.06\,\dot{\phi}^{1/2}$

$\Lambda_2 < \infty$ rules out single-field $\quad \Lambda_2 > \left(\frac{r}{0.04}\right)^{1/2} M_{\rm pl}$

CF26: *Will astrophysical systematics derail our ambitious CMB goals?*



- Inflationary Signal: Two “foregrounds”
  - Lensing: Physics well understood. Only modest removal needed
  - Galactic dust and synchrotron: Comparable to signal
    - Remove with multiple frequencies: 40, 90, 150, 220 GHz
    - Achievable factor 10 in amplitude required

CF30. The study of cosmic structure may allow us to measure neutrino masses sufficiently accurately to determine the hierarchy. How realistic is this, what assumptions are needed, and when is this likely to happen?

(What can the cosmos tell us about neutrinos? What assumptions need to be made?)

- A lot! And they are guaranteed to see something (or learn something amazing!) once they get to sums of neutrino masses below $\sqrt{\Delta m^2_{13}} > 0.04$ eV. And this is expected to happen very soon (as "in this decade").
- Assumptions are (i) particle physics is as we understand it (but beware of dark matter and the unexpected), (ii) the thermal history of the Universe (GR + Stat Mech) is as we understand it (again, room for surprises).
- Level of "trustworthiness" will grow, especially once/if different probes (different dependence on cosmological parameters, systematics) point to the same answer!

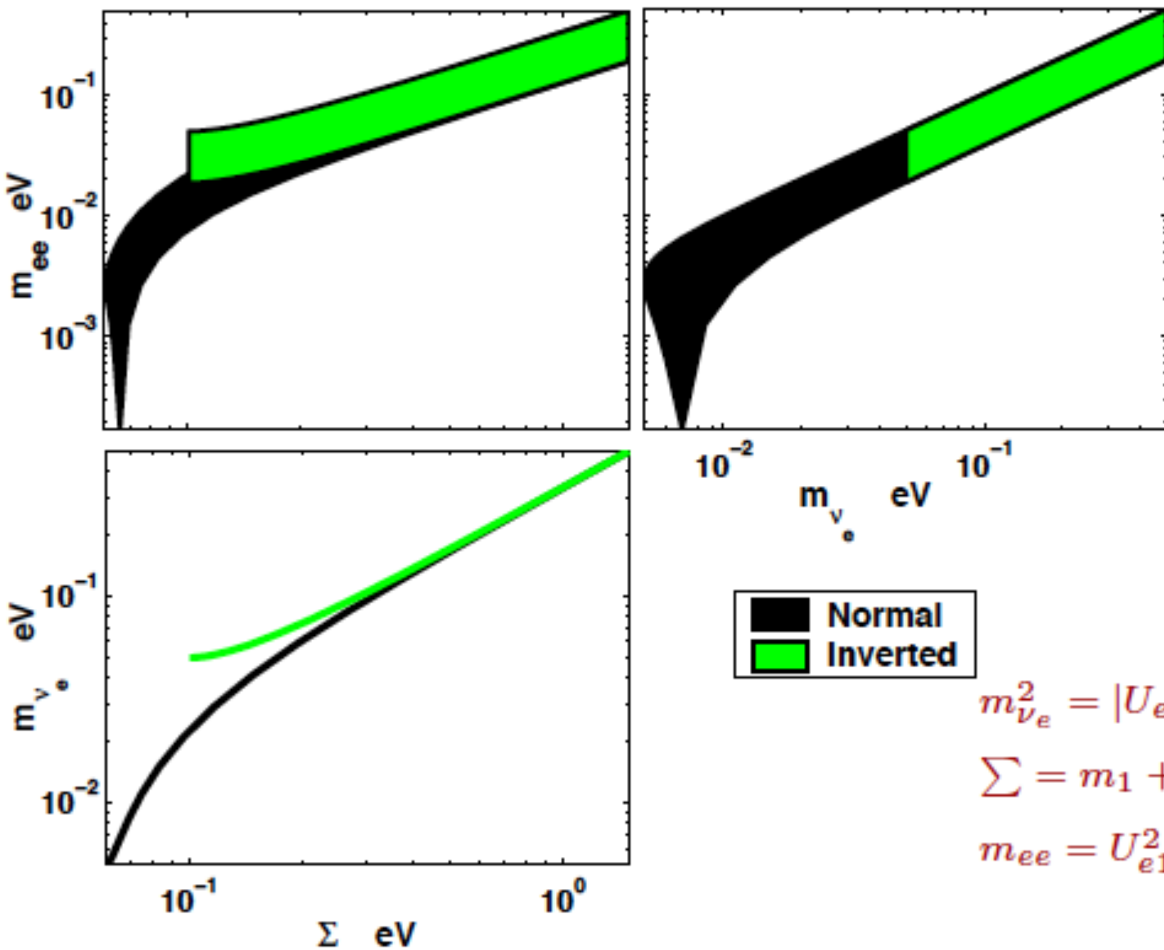
Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	$0.2 - 0.05$	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	$0.1 - 0.006$	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST
Core-Collapse Supernovae	∞	$\theta_{13} > 0.001^*$	Emergent ν spectra	SuperK [98], ICECube[90]	Noble Liquids, Gadzooks [7]

Table I: Cosmological probes of neutrino mass. "Current" denotes published (although in some cases controversial, hence the range) 95% C.L/ upper bound on $\sum m_\nu$ obtained from currently operating surveys, while "Reach" indicates the forecasted 95% sensitivity on $\sum m_\nu$ from future observations. These numbers have been derived for a minimal 7-parameter vanilla+m_ν model. The six other parameters are: the amplitude of fluctuations, the slope of the spectral index of the primordial fluctuations, the baryon density, the matter density, the epoch of reionization, and the Hubble constant.

* If the neutrinos have the normal mass hierarchy, supernovae spectra are sensitive to $\theta_{13} \sim 10^{-3}$. The inverted hierarchy produces a different signature, but one that is insensitive to θ_{13}.

[Abazajian *et al*, arxiv:1103.5083]

Combining the Different Neutrino Mass Observables – Fundamental



$$m_{\nu_e}^2 = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$

$$\sum = m_1 + m_2 + m_3$$

$$m_{ee} = U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3$$

[Illustrative only, for $U_{e3} = 0$, $\Delta m_{13}^{2+} = +2.50 \times 10^{-3}$ eV^2, $\Delta m_{13}^{2-} = -2.44 \times 10^{-3}$ eV^2]

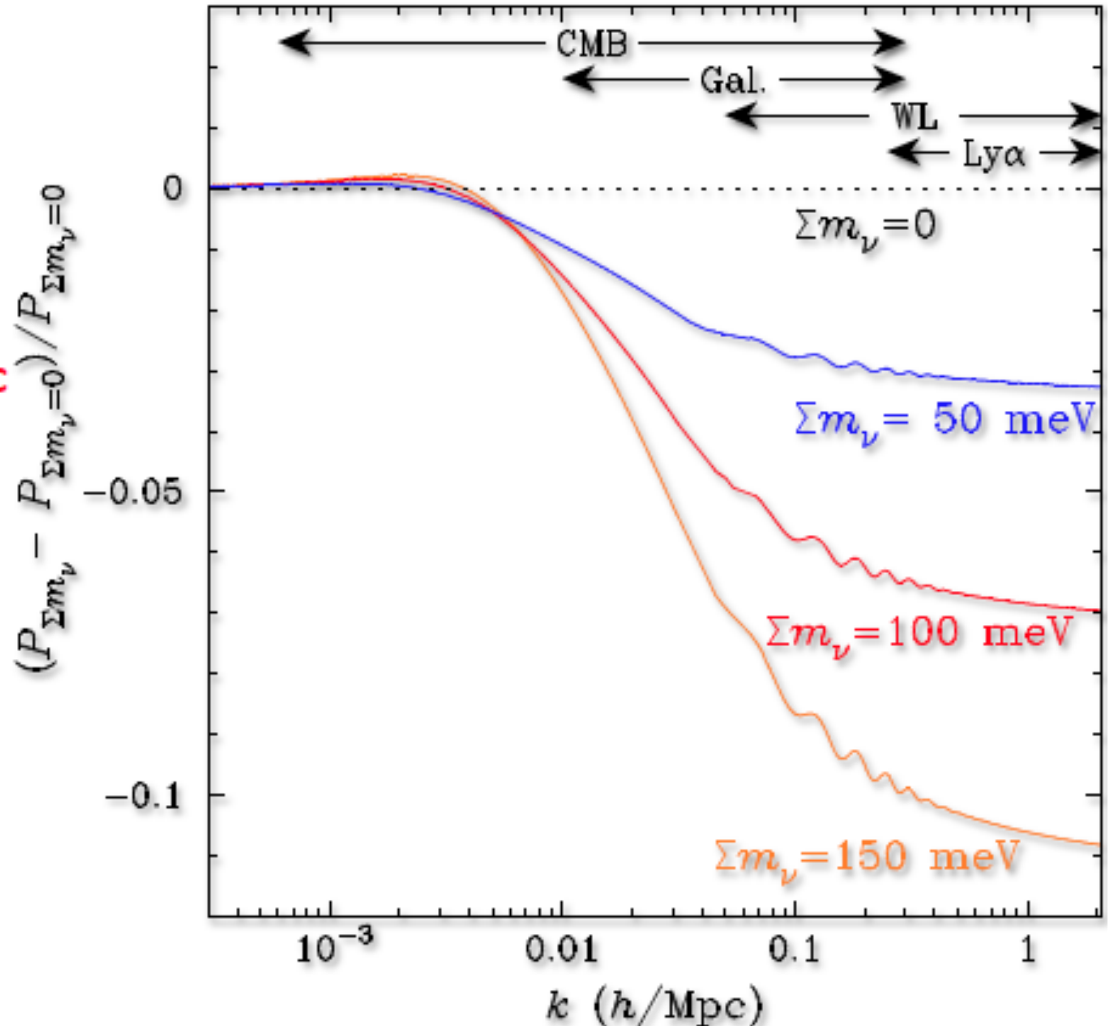
CF30: How realistic is detecting the mass hierarchy of neutrinos with cosmology, <u>what assumptions are needed,</u> and when is this likely to happen?

Neutrino mass induces a specific feature in the matter power spectrum detectable by multiple probes and different epochs, which check consistency.

The suppression of the atmospheric neutrino scale is of order 5% and is detectable at high significance by CMB-S4 lensing and DESI.

Assumptions include:

1. Statistical mechanics is valid
2. GR is valid cosmologically
3. Weak-field gravity is valid



If it is inconsistent with the lab, then <u>*something else very interesting must be happening!*</u>

CF31: What is the projected accuracy of the sum of neutrino masses & N_{eff} from the cosmic frontier in 2020 and 2025 and 2030?

DATASET	$\sigma\left(\sum m_\nu\right)$ [meV]	$\sigma\left(N_{\rm eff}\right)$
TODAY:		
Planck + BOSS BAO	100	0.34
2020:		
Planck + eBOSS galaxy clustering	36/52	0.13/0.16
Stage-III CMB + BOSS BAO	60	0.06
2025:		
Planck + DESI galaxy clustering	17/24	0.08/0.12
Planck + LSST	23	0.07
Stage-IV CMB + DESI BAO	16	0.02

Cosmic constraints are complimentary to terrestrial experiments, and will be at a sensitivity that they can precisely test predictions; either confirming the standard model or indicating new physics.